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**Final Report**

**1 September 1990 - 1 September 1993**

**on**

**INITIATION AND MODIFICATION OF REACTION**

**BY ENERGY ADDITION:**

**KINETIC AND TRANSPORT PHENOMENA**

**by**

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13. ABSTRACT (Maximum 200 words)  Work has been pursued, by application of the fundamental principles of chemical kinetics and fluid transport, on proof of principle for a novel oblique-detonation-wave engine (ODWE) as an alternative to a mixing-controlled supersonic combustor. The concept involves the nonintrusive stabilization of a conical detonation wave. Laser technology permits the rapidly repeated pulsed deposition of energy at a fixed site on the axis of symmetry of a supersonically flowing, combustible mixture. Each pulse suffices for the direct initiation of a radially outwardly propagating, Chapman-Jouguet detonation wave. The interaction of the individual spherical waves, as the periodic train is convected by the flow, results in a nonintrusively stabilized conical wave, as the time interval between the very brief pulses decreases. The detonated gas may be expanded in a supersonic nozzle (of practical length) for discharge at ambient pressure, such that thrust is generated.  The work combined: (1) theoretical modeling of the flow field for a homogeneous mixture; and (2) laboratory demonstration by ArF-excimer laser of direct initiation in readily detonable mixtures initially at both atmospheric and subatmospheric pressures. The results were encouraging: for example, the laser energy per pulse shown to suffice for direct photochemical initiation is exceptionally small, and the entropy rise (a measure of the energy unavailable to do useful work) is minimized relative to that for other ODWE designs.  The remaining tasks were prioritized to be: experimentally, the direct initiation by excimer laser of detonation in less readily detonable, more practically interesting fuel-air mixtures (possibly with the aid of photodissociative sensitizers); theoretically, the prediction of the consequences of the inevitably imperfect mixing of fuel with the intake air (the well-mixed fraction of the throughput entering the combustor proper would be reacted in a conical detonation wave, and the not-well-mixed fraction would undergo diffusive burning downstream of the wave).				
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## **PREFACE**

The authors wish to thank Julian Tishkoff, the contract technical monitor, for constructive suggestions and for helpful contacts with the high-speed-propulsion technical community.

## 1.0 Technical Objective

High-speed air-breathing combustion systems necessitate the release of chemical energy during the relatively brief residence time of reactants within combustors of practical length: mixing, ignition, and chemical reaction must be achieved in a relatively short time. Towards this challenge, we have developed the concept of a supersonic combustor based on a nonintrusively stabilized oblique (conically configured) detonation wave. The conical wave is the result of the interaction of a train of spherical detonation waves, each initiated (in a very-fast-flowing gaseous fuel/air mixture) by energy deposition from a rapidly repeated pulsed laser. We address the proof-of-principle technology for such a supersonic combustor, in which relatively small entropy rise is incurred, by fundamental experiments and analyses.

Specifically, for fuel/air mixtures of practical interest, we seek to fulfill the need for data on the minimum deposition energy, minimum pulse duration, and minimum deposition volume required for the direct (nonintrusive) initiation of a Chapman-Jouguet (CJ) detonation; i.e., we seek data on direct initiation without either overdriving (blast-wave decay) or underdriving (deflagration-to-detonation transition). We also examine the consequences for engine performance of inhomogeneity and off-stoichiometry in the cold mixture.

## 2.0 Technical Summary

Among the future air-breathing-propulsion requirements of the U.S. Air Force (and of most of its counterparts in the technically more advanced nations around the globe), a high priority is accorded to the development of a supersonic combustor (Rosen 1991; Kandebo 1992). Such a combustor is of interest both as: (1) the final stage of a sequence of engine configurations designed to accelerate a vehicle from subsonic through transonic to appreciably supersonic speeds; and/or (2) the last air-breathing stage of a dual-mode propulsion system in which a rocket is used to complete the attainment of earth orbit. The predominant effort on supersonic combustors over the past three decades has been dedicated to the development of a scramjet based on supersonic diffusion flames (mixing-controlled combustion) (Waltrup 1987; Billig 1992). However, it is now well recognized, as a consequence of much fundamental theoretical and experimental effort, that the slow growth of mixing layers at supersonic speed is a not-easily-overcome challenge. Attempts to generate external disturbances to enhance the natural rate of engulfment and then homogenization of fresh fluid into a high-speed mixing layer have met with limited success.

In this project, we have investigated what new opportunities in air-breathing propulsion are afforded by the rapid evolution of laser technology. Lasers facilitate the highly localized, nonintrusive deposition into absorptive media of monochromatic energy in very brief pulses.

(The subject of novel nonintrusive diagnostic instrumentation powered by lasers is distinct, and was not the topic of the project). The primary opportunity afforded by lasers for air-breathing propulsion concerns ignition of combustible gaseous mixtures.

The first three years of our effort were dedicated to the nonintrusive initiation of deflagration waves by ArF-excimer laser (Chou and Zukowski 1991; see also Carrier et al. 1991a, 1991b). We found that the amount of energy required for ignition in simple-hydrocarbon/air stoichiometric mixtures could be reduced from spark-ignition levels by the use of laser-initiated photoselective chemistry, with trace-level sensitizers such as  $\text{NH}_3$  or  $\text{C}_2\text{H}_2$ ; furthermore, the enhancement in the amount of energy required for ignition, as the equivalence ratio of the mixture is varied from unity, is notably more modest for laser ignition than for spark ignition: a range of about 135-155 mJ/cm<sup>3</sup> for laser ignition was experimentally determined (Chou and Zukowski 1991) in our work, in comparison with a typical spark ignition level (thermal deposition) of 430 mJ/cm<sup>3</sup>. These results drew attention from the reciprocating-piston-type internal-combustion-engine community, especially the segment of that community concerned with the use of innovative high-octane-number, difficult-to-ignite fuels (such as the Gas Research Institute, Southern California Gas Company, Brooklyn Gas, etc., all of whom seek to promote the use of natural gas for both transportation-type and stationary, power-producing-type IC engines).

However, we soon became aware that the use of nonintrusive energy deposition for the direct initiation of a detonation wave in a gaseous mixture is more pertinent for the supersonic-combustor applications of interest to the Air Force (compare Figs. 1 and 2) (Carrier, Fendell, and Sheffield 1990; Fendell, Kung, and Sheffield 1992). Thus, over the past three years, we have worked on a novel variant of the oblique-detonation-wave engine (ODWE). A summary of significant results achieved along this path of investigation, and the list of publications in which we have presented our work, are shown in Fig. 3. Some form of an ODWE has been considered for about four decades as a possibly viable alternative to a scramjet predicated on mixing-controlled combustion. It may seem paradoxical that interest has persisted in a detonation-based supersonic combustor, since the development of a combustor based on mixing-limited burning has proven challenging. We shall return to the topic of the formation of an effectively homogeneous combustible mixture at appreciably supersonic flight speed.

**Analysis Results - Conceptual Combustor Design.** We summarize here the concept for the simple supersonic combustor (with no moving parts in the flow stream) that we have investigated (Fig. 4) (Carrier, Fendell, McGregor, Cook, and Vazirani 1992), and the scope of the analysis carried out in support of the concept. The first step is to add gaseous fuel to ambient air captured in a simple pipe-type inlet, to form a homogeneous combustible mixture. We seek to minimize the increase of static



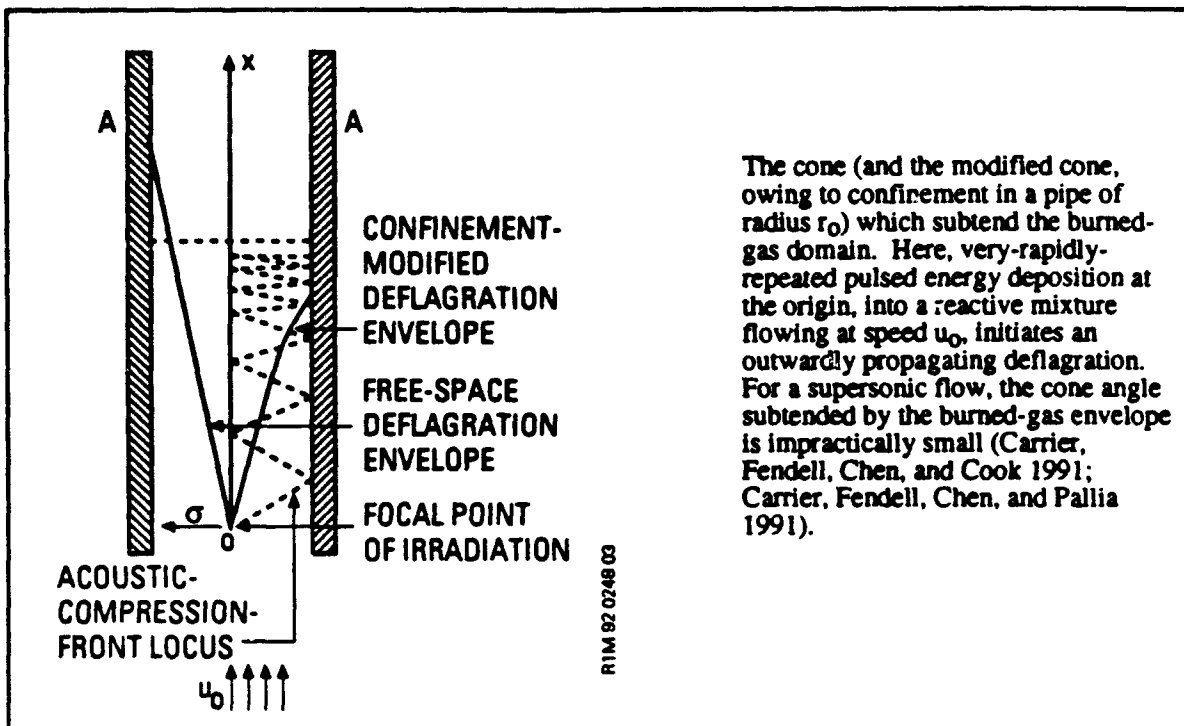


Figure 1. Schematic of Energy Deposition in a High-Speed Flow in a Pipe

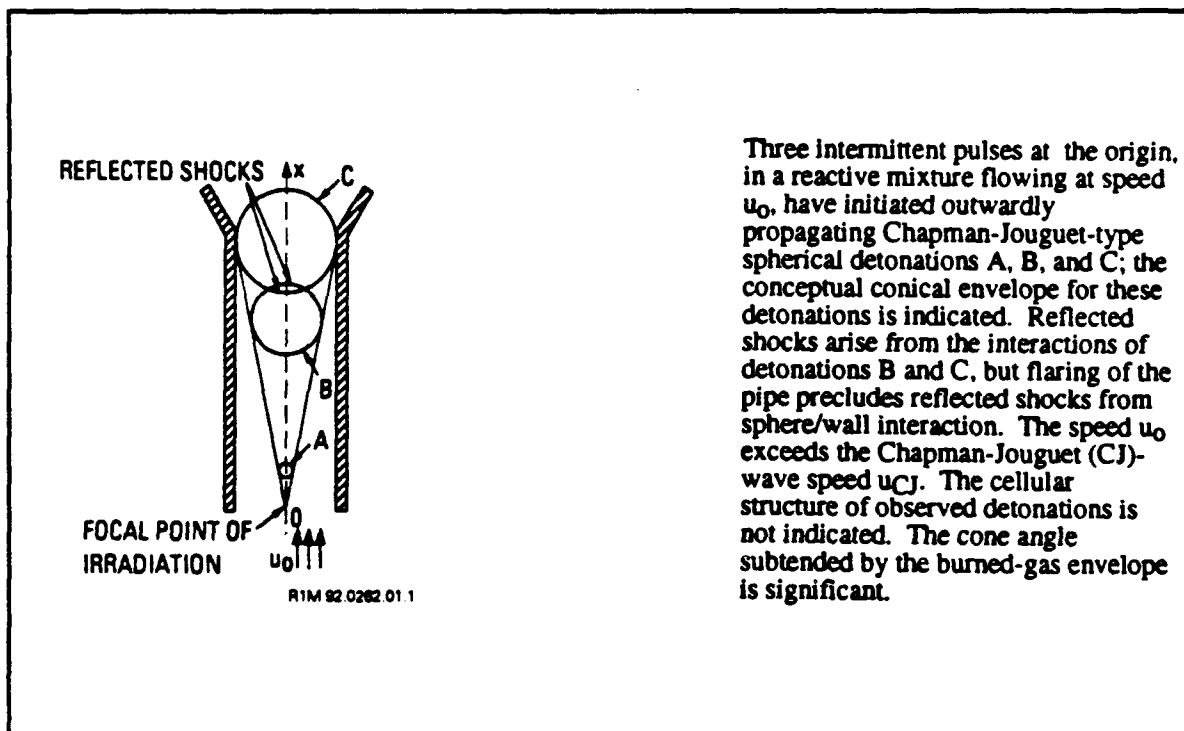


Figure 2. Illustration of Pulsed Detonation Waves in a Flared Pipe

#### A. SUMMARY OF SIGNIFICANT RESULTS

- Photochemical ignition of deflagration in sensitized fuel-air mixture by ArF-excimer laser may be achieved with less energy density than thermal ignition, especially at off-stoichiometric equivalence ratios (Ref 5, below).
- An unsteady convective-reactive-diffusive description of spherical laminar flame propagation, according to Shvab-Zeldovich-type formulation, is conveniently accessible in quadrature form (Ref 2, 3).
- Nonintrusive energy deposition in a flowing combustible mixture might stabilize a deflagration wave, but the direct initiation of detonation seems required for practical supersonic combustion (Ref 1, 4).
- Achievement of the direct initiation of a periodic train of spherical Chapman-Jouguet detonation waves in a supersonically flowing mixture would permit stabilization of a conical wave; conceptualization of a novel oblique-detonation-wave combustor then seems straightforward (Ref 6).
- Expansion of detonated gas, in the above-described combustor, to ambient pressure for discharge to the atmosphere via a supersonic nozzle of practical length and breadth, seems achievable (Ref 7).
- Very rapidly repeated pulsing of a laser source is desirable, to minimize entropy production by reflected shocks, formed when neighboring spherical detonations in a train interact (Ref 8).
- Direct photochemical initiation of detonation in gaseous mixtures without overdriving is demonstrable, with notably small total energy per pulse, by use of an ArF-excimer laser (Ref 10).
- A key issue for the feasibility of a laser-initiated conical-detonation-wave-based supersonic combustor is the degree of fuel mixedness with intake air achievable (vis-a-vis the degree required for efficient burnup) (Ref 9).

#### B. SUMMARY OF PUBLICATIONS AND PRESENTATIONS

1. Carrier, G. F., Fendell, F. E. and Sheffield, M. W., 1990. "Stabilization of a premixed planar flame by localized energy addition," AIAA J. 28, p. 625.
2. Carrier, G., Fendell, F., Chen, K. and Cook, S., 1991. "Evaluating a simple model for laminar-flame-propagation rates. II. Spherical geometry," Combust. Sci. Tech. 79, p. 229.
3. Carrier, G., Fendell, F., Chen, K. and Pallia, C., 1991. "Evaluating a simple model of laminar-flame-propagation rates. I. Planar geometry," Combust. Sci. Tech. 79, p. 207.
4. Fendell, F. E., Kung, E. Y. and Sheffield M. W., 1992. "Flame configuration associated with localized energy addition to a flowing combustible mixture," J. Propulsion Power 8, p. 464.
5. Chou, M.-S. and Zukowski, T. J., 1991. "Ignition of H<sub>2</sub>/O<sub>2</sub>/NH<sub>3</sub>, H<sub>2</sub>/air/NH<sub>3</sub> and CH<sub>4</sub>/O<sub>2</sub>/NH<sub>3</sub> mixtures by excimer-laser photolysis of NH<sub>3</sub>," Combust. Flame 87, p. 191.
6. Carrier, G., Fendell, F., McGregor, R., Cook, S. and Vazirani, M., 1992. "Laser-initiated conical detonation wave for supersonic combustion," J. Propulsion Power 8, p. 472 (presented at the AIAA 29th Aerospace Sciences Meeting, Reno, NV, January 1991).
7. Fendell, F., Mitchell, J., McGregor, R., Magiawala, K. and Sheffield, M., 1992. "Laser-initiated conical detonation wave for supersonic combustion. II," AIAA Paper 92-0088, American Institute of Aeronautics and Astronautics, Washington, DC (presented at the AIAA 30th Aerospace Sciences Meeting, Reno, NV, January 6-9; to appear, J. Propulsion Power).
8. Carrier, G. F., Fendell, F. E. and Chou, M.-S., 1992. "Laser-initiated conical detonation wave for supersonic combustion. III," AIAA Paper 92-3247, American Institute of Aeronautics and Astronautics, Washington, DC (presented at the 28th Joint Propulsion Conference, Nashville, TN, July 6-8).
9. Carrier, G. F., Fendell, F. E. and Chou, M.-S., 1992. "Laser-initiated conical detonation wave for supersonic combustion - a review," 2nd ICASE/NASA Langley Workshop on Combustion, Newport News, VA, October 12-14 (to be published, Springer-Verlag).
10. Chou, M.-S., Fendell, F. E. and Behrens, H. W., 1993. "Theoretical and experimental studies of laser-initiated detonation waves for supersonic combustion," Paper 1862-05, SPIE International Symposium on Laser Applications in Combustion and Laser Diagnostics, Los Angeles, CA, January 16-23.

Figure 3. Summary of Key Technical Results and List of Publications Resulting from Work on the Initial and Current Three-Year Research Contracts

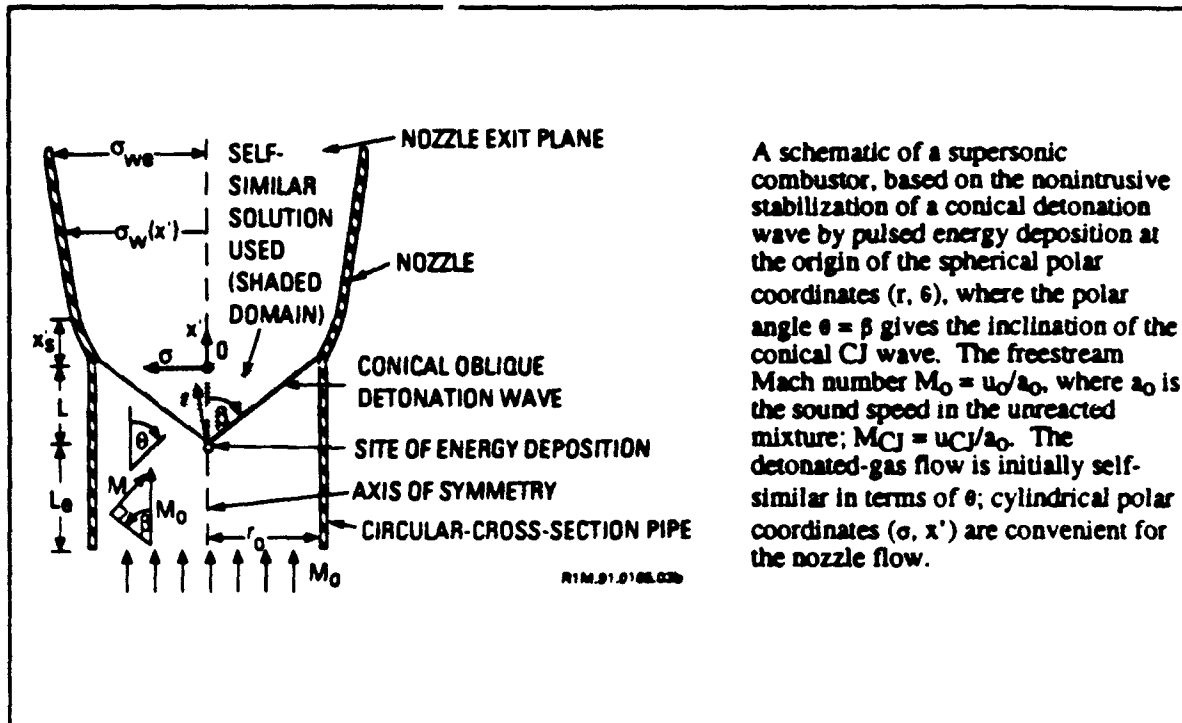


Figure 4. Schematic of Supersonic Oblique-Detonation-Wave Combustor

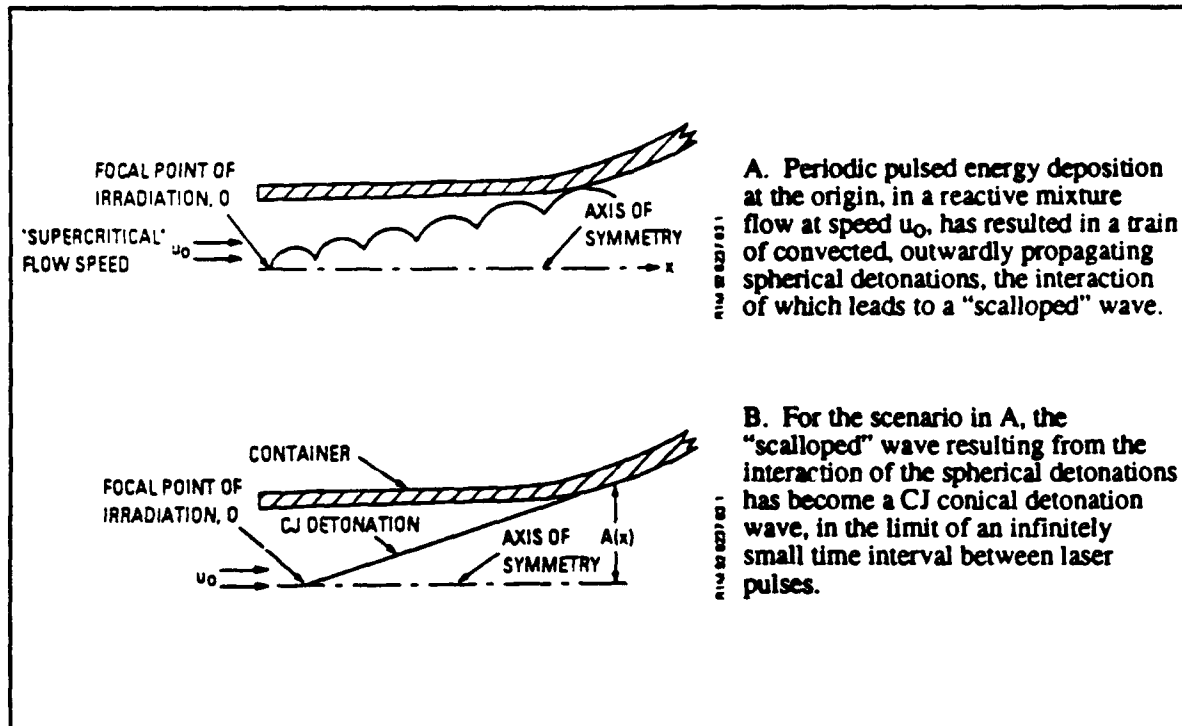


Figure 5. Illustration of Similarity of Periodic Pulsed Detonation Waves to a Conical Detonation Wave

temperature during fuel admixture, lest premature shock-induced ignition occur. At a fixed site on the axis of symmetry, we periodically deposit energy by laser pulse, each pulse initiating a (spherically) radially outwardly propagating detonation wave in the supersonically flowing mixture. The interaction of the individual spherical detonation waves in the train results in a corrugated front (Fig. 5A), which approaches a conical-wave configuration (Fig. 5B) as the time interval between pulses approaches zero. We should not pulse so frequently that we wastefully deposit two pulses in essentially the same element of flowing mixture; however, the interaction of two neighboring spherical detonations results in entropy-producing reflected shocks in the already-burned mixture (Fig. 6) (Carrier, Fendell, and Chou 1992), so a rapid rate of laser pulsing is desired (Figs. 7-10). The pipe wall is flared at the site of proximity with the nonintrusively stabilized conical detonation wave (Fig. 4), again to avoid entropy-producing reflected shocks in the burned gas, but also to avoid the material problems associated with a high gas temperature arising near any portion of the combustor surface. A simple, roughly conically shaped diffuser (Fig. 4) is adjoined smoothly to the pipe to develop thrust, and to permit discharge (of the chemically reacted mixture) uniformly at ambient pressure. Our preliminary indications, under highly idealized modeling, are that such a supersonic combustor could be designed with feasible length and radius (Fendell, Mitchell, McGregor, Magiawala, and Sheffield 1992).

Many aspects of the combustor concept proved amenable to fairly straightforward quantitative analysis. For example, the flow of the reacted mixture just downwind of the conical wave (Fig. 4) admits selfsimilar solution in terms of a spherical polar angle  $\theta$ , with  $\beta \geq \theta \geq 0$ , where  $\theta = 0$  is directly downwind along the axis of symmetry, and  $\theta = \beta$  is the (readily computed) angle of inclination of a Chapman-Jouguet wave to the direction of the oncoming unreacted mixture. However, simplicity suffices only to a certain extent: (1) downwind of the site of detonation-wave/cylindrical-inlet-pipe proximity, the "domain of dependence" of the reacted flow is characterized by a finite physical dimension (the pipe radius), and the analytic advantages afforded by similarity do not hold for the portion of the flow field further downwind; and (2) a finite cellular structure arises for all real detonations (Lee 1977, 1984), so only for certain engineering purposes may the conical detonation wave be approximated adequately as a discontinuity (without structure) at which chemical energy is added to the flow.

Such a supersonic combustor, based on a laser-initiated conical detonation wave, is limited to finite range of flight Mach number. The flight Mach number may not be so small that the CJ-wave speed exceeds the speed of the throughput entering the combustor proper, or else a detonative "flash back" is incurred. On the other hand, the flight Mach number may not be so large that even modest nonisentropic deceleration of captured air results in static temperatures so high that admixture of fuel

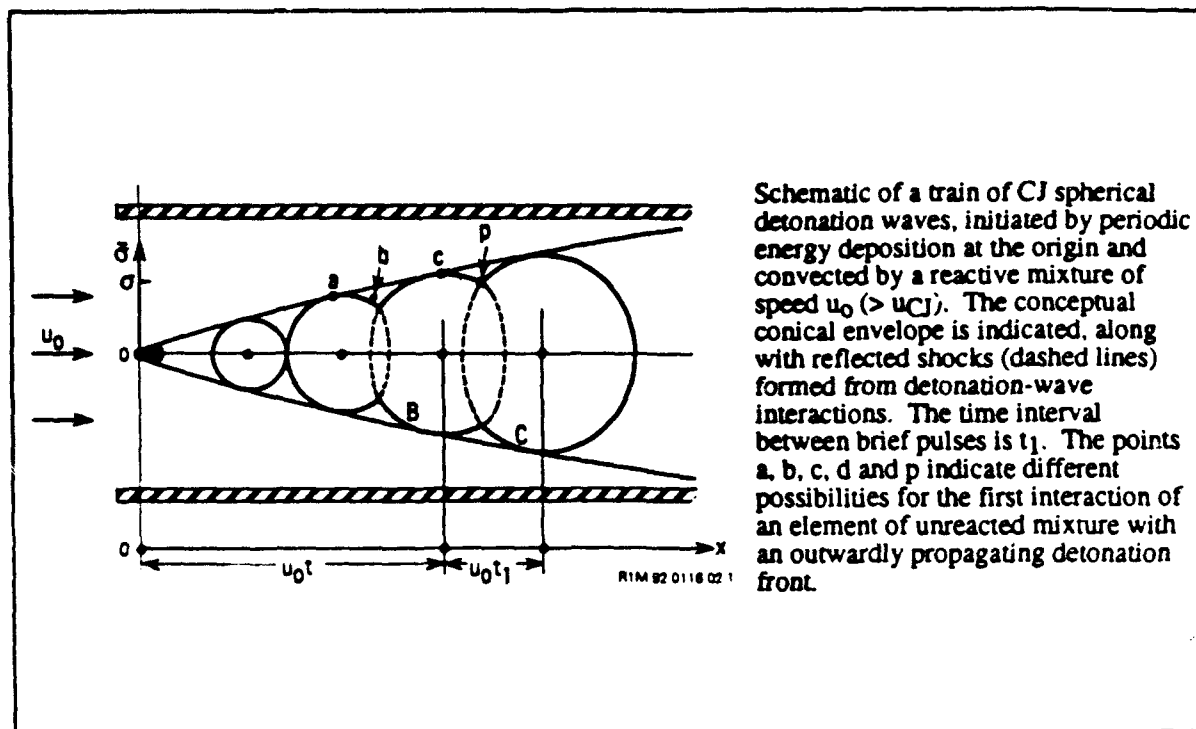


Figure 6. Schematic of Spherical Detonation Wave Train in a Straight Pipe

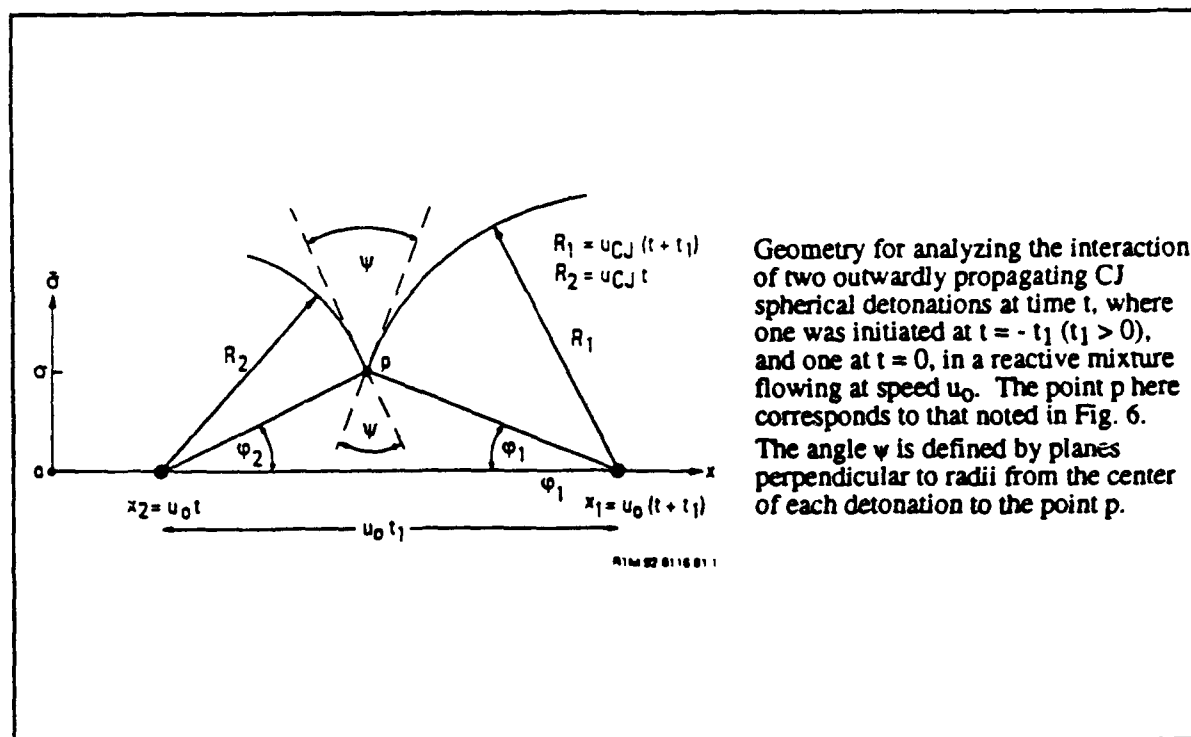


Figure 7. Spherical Detonation Wave Analysis Geometry

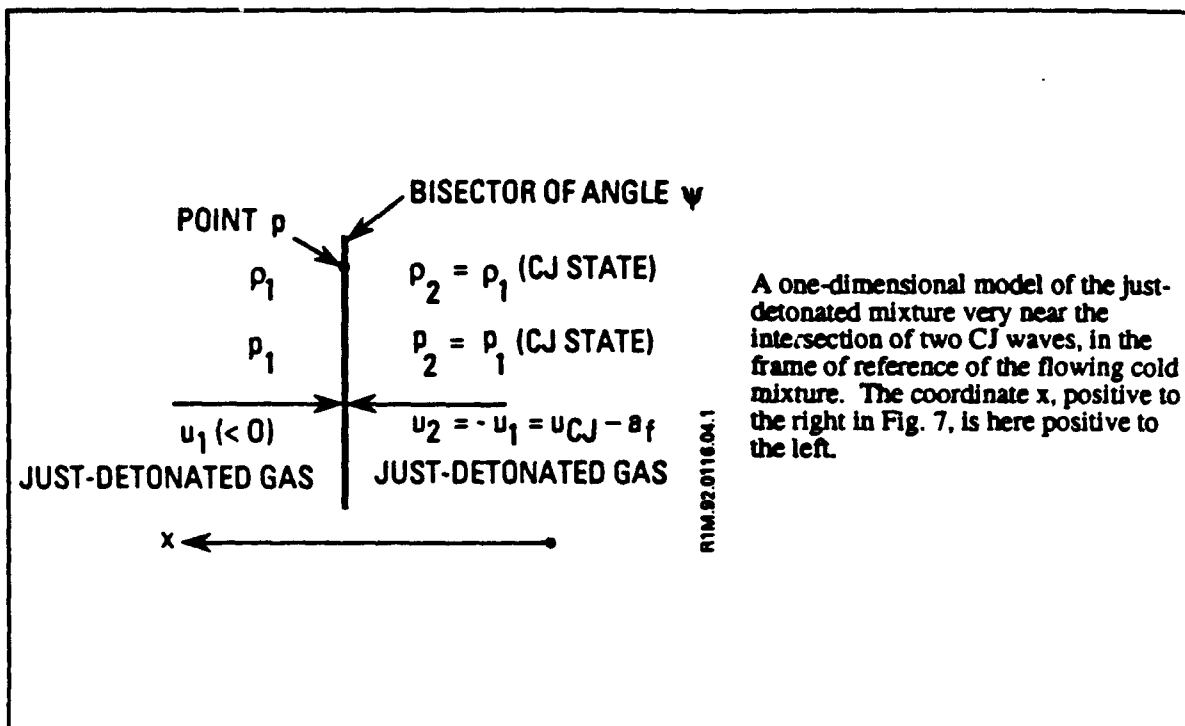


Figure 8. One-Dimensional Model for Analysis of Detonation-Wave Interactions

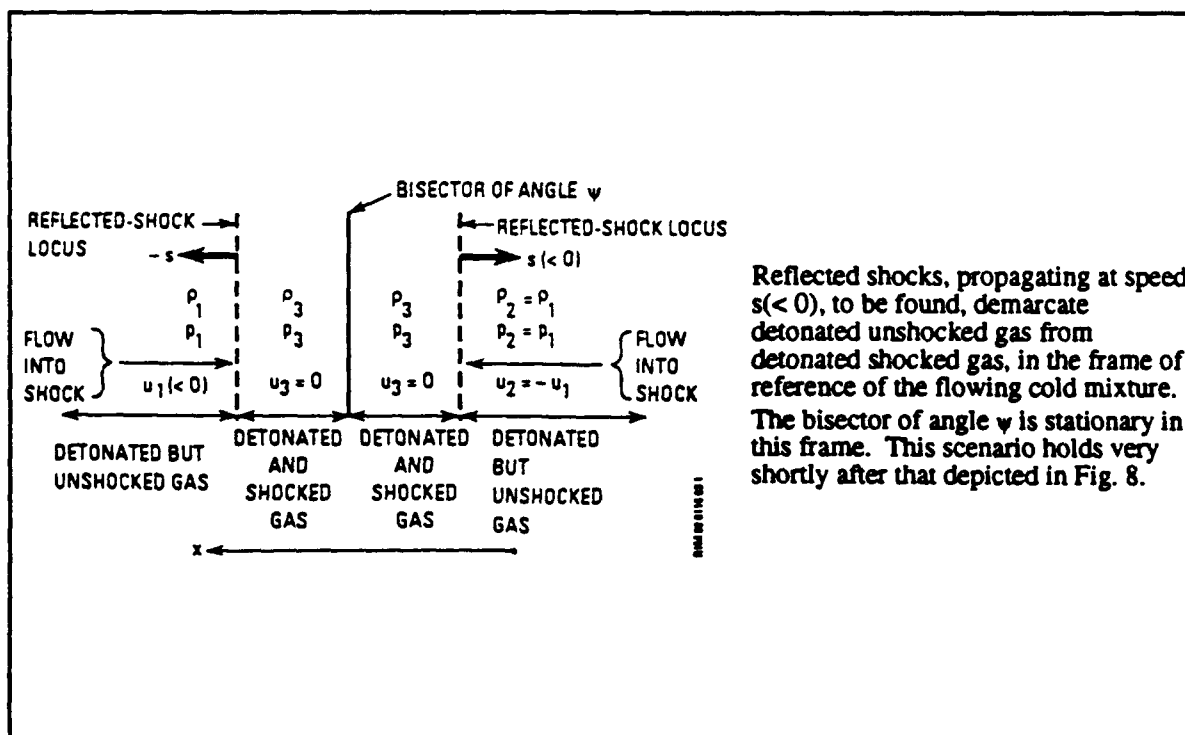
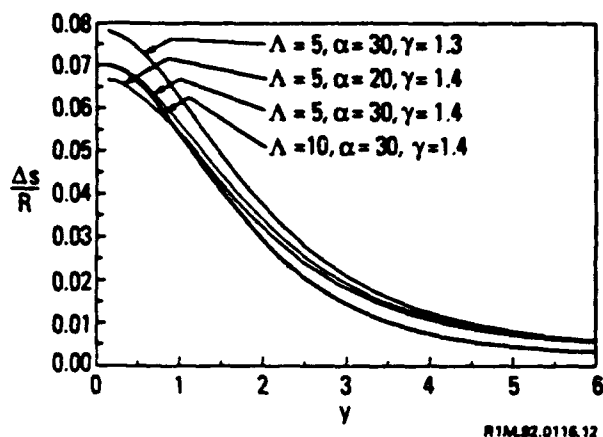


Figure 9. One-Dimensional Model for Analysis of Reflected-Shock Interactions



The change in entropy  $\Delta s$  across one of the reflected shocks depicted in Fig. 9, as a function of the parameter  $\gamma (= \sigma/(u_{CJ} t_1))$ , where  $\sigma$  is the value cylindrical-radial coordinate of the point p. The parameter  $\Lambda (= u_0/u_{CJ}) > 1$ ;  $\alpha = q/(p_0/\rho_0)$ , where  $q$  denotes the chemical exothermicity per mass of mixture, and  $p_0$  and  $\rho_0$  denote the cold-mixture pressure and density, respectively; and  $\gamma$  denotes the ratio of specific heats. The normalization factor  $R$  is the gas constant. Minimizing the interpulse interval, minimizes the entropy increase owing to reflected shocks.

Figure 10. Entropy Change Across Reflected Shocks

results in premature ignition, upwind of the laser-energy-deposition site. There are also limitations on the ambient pressure. The cellular scale of observed detonations tends to vary inversely with the pressure of the unreacted mixture (Nettleton 1987), and the fact that several cells need to be encompassed for a stable detonation implies an increase in the physical scale of the combustor at sufficiently low ambient pressure. On the other hand, higher ambient pressure implies higher flow density and consequently higher heat-transfer challenges for the combustor components. Tradeoffs centered on the ambient-pressure level are commonly encountered in supersonic-combustor design.

**Experimental Results - Laser-Initiated Detonation.** As part of our work, we contributed to the proof of principle of the novel-ODWE technology by successfully using an excimer laser to initiate detonations in several fuel/oxidizer mixtures (Chou, Fendell, and Behrens 1993). The experiments were carried out in an open system at one atmosphere (Fig. 11). A flat-flame burner is used to achieve uniform flows of, for example, an acetylene/oxygen mixture. The measured detonation-wave velocity (approximately 2.3 - 2.9 km/s) agrees well with the CJ-wave speed (Fig. 12). The measured peak pressure is  $103 \pm 8$  atm if the normal to the pressure-transducer face is aligned with the propagation direction of the detonation wave, and is  $34 \pm 4$  atm (as predicted by CJ theory) if the normal to the transducer is perpendicular to the propagation direction of the wave. These values indicate the reflection of a strong wave. From high-speed IMACON photographs (Fig. 13), we infer, by examining the rate of expansion of the detonation-wave front (Fig. 14), that the detonation is neither overdriven nor underdriven.

The incident laser energy ( $12 \pm 4$  mJ) needed for the direct initiation of detonation of a ( $C_2H_2 + 1.5 O_2$ ) mixture is  $12 \pm 4$  mJ (Fig. 15), of which the absorbed laser energy is estimated to be about 8 mJ. This critical energy is substantially lower than that required by use of a conventional spark, chemical explosive, or exploding wire. This small critical energy is partly owing to relatively strong absorption by  $C_2H_2$  of the ArF-laser radiation, and partly to the tight focusing with a very-short-duration pulse (about 20 ns). Conceivably, key chemical reactions are promoted by the reactive photofragments  $C_2H$  and  $H$ , generated by the photolysis of  $C_2H_2$ .

The critical energies for  $C_2H_2$ /air and other fuel/air mixtures are expected to be much larger. The critical energy for  $C_2H_2/O_2/N_2$  is about 400 mJ for an  $N_2/O_2$  ratio of about 1.1 (Fig. 16). With relatively large energy deposition, we initiated detonation in  $H_2/O_2$  and  $CH_4/O_2$  by adding  $C_2H_2$  to these mixtures as a sensitizer (Fig. 17).

We also achieved direct laser-initiated detonation in a tube at reduced pressures (fig. 18), and also detonation after a relatively long delay time by use of laser energy smaller than the critical value



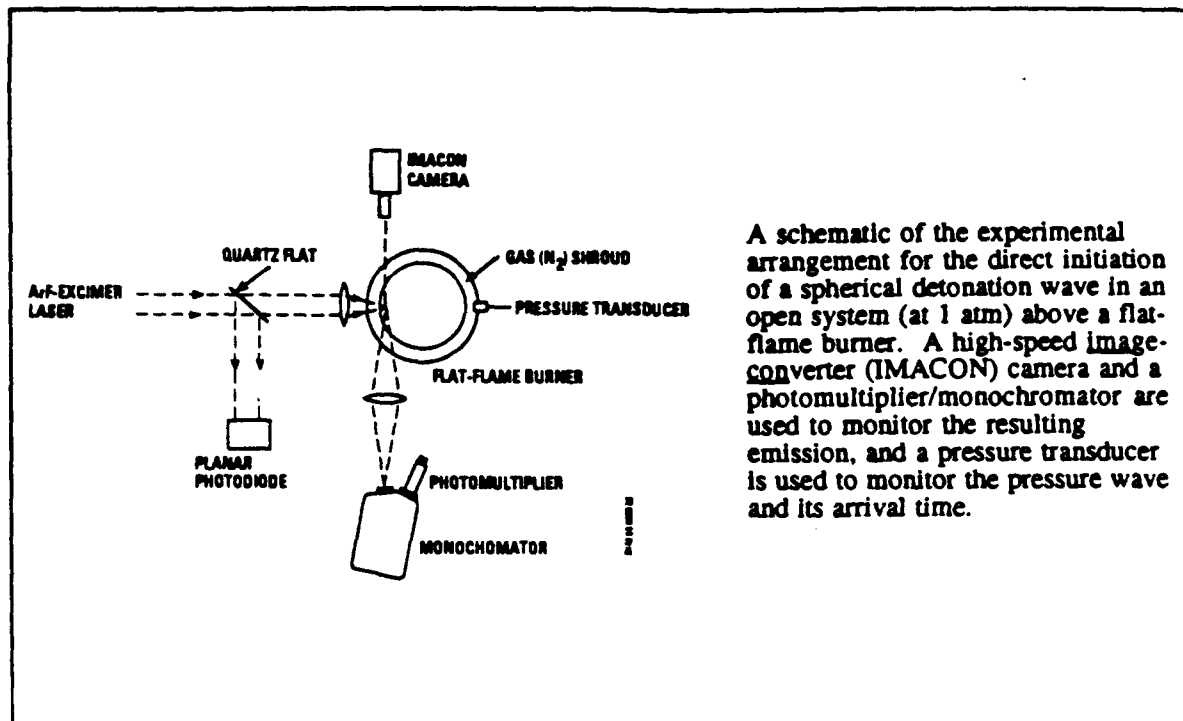


Figure 11. Experimental Arrangement for Initiation of a Spherical Detonation Wave

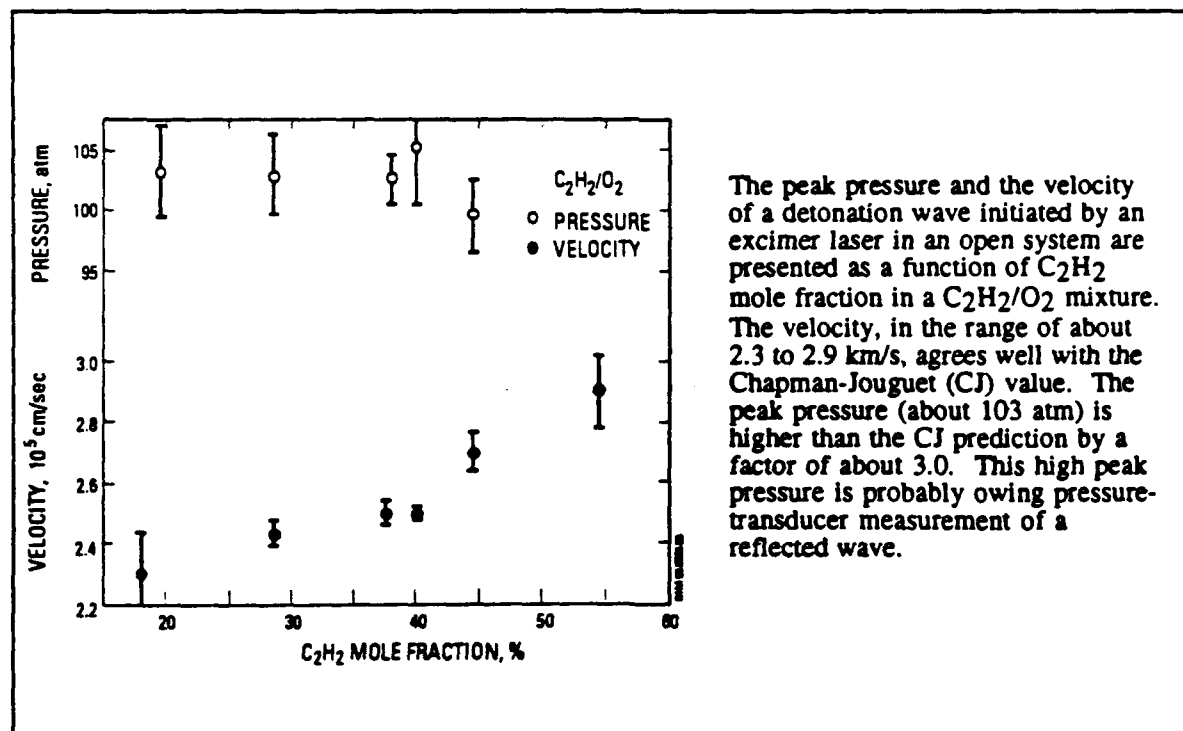


Figure 12. Variation of Peak Pressure and Velocity with Mixture Ratio

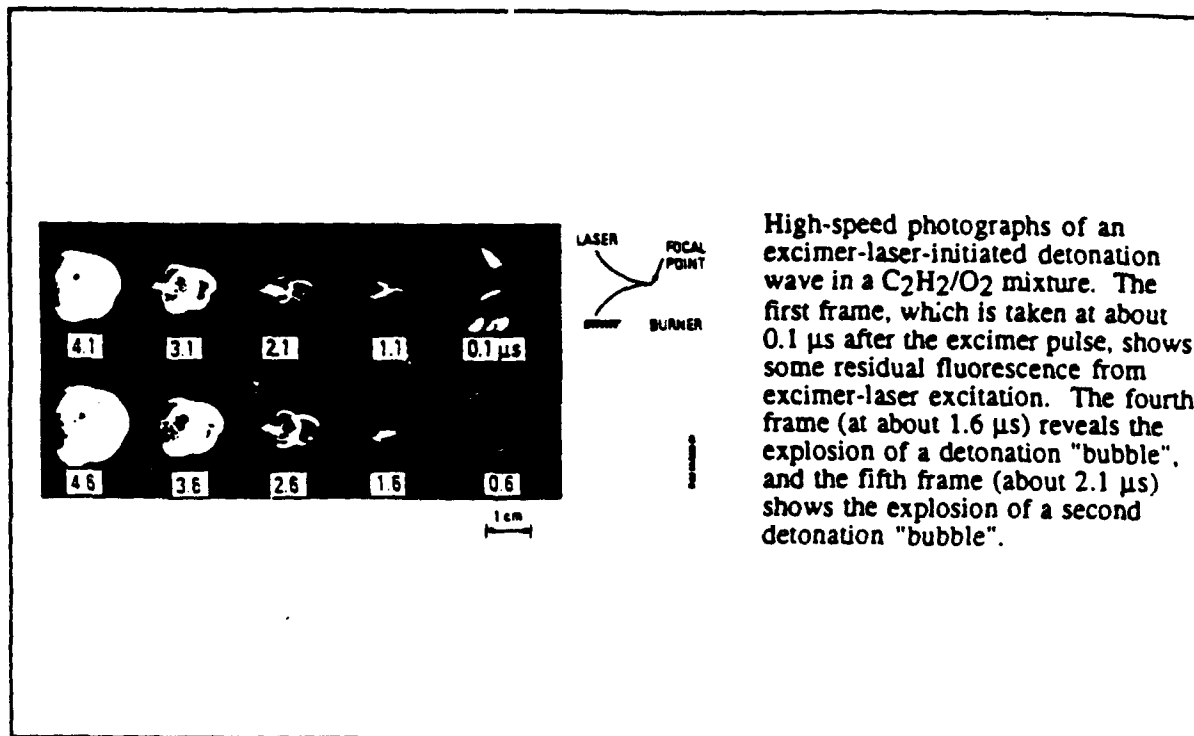


Figure 13. High-Speed Photographs of Excimer-Laser-Initiated Spherical Detonation Waves in  $C_2H_2/O_2$  Mixtures

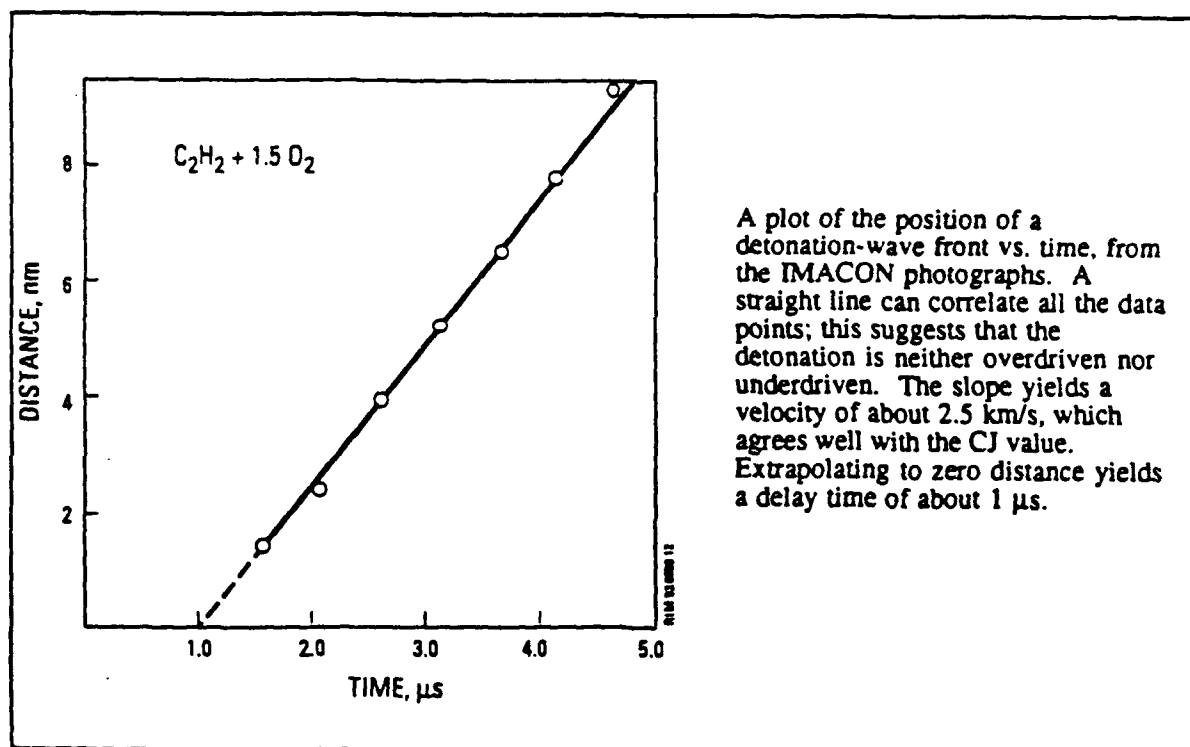


Figure 14. Wave-Front Position vs. Time from High-Speed Photographs

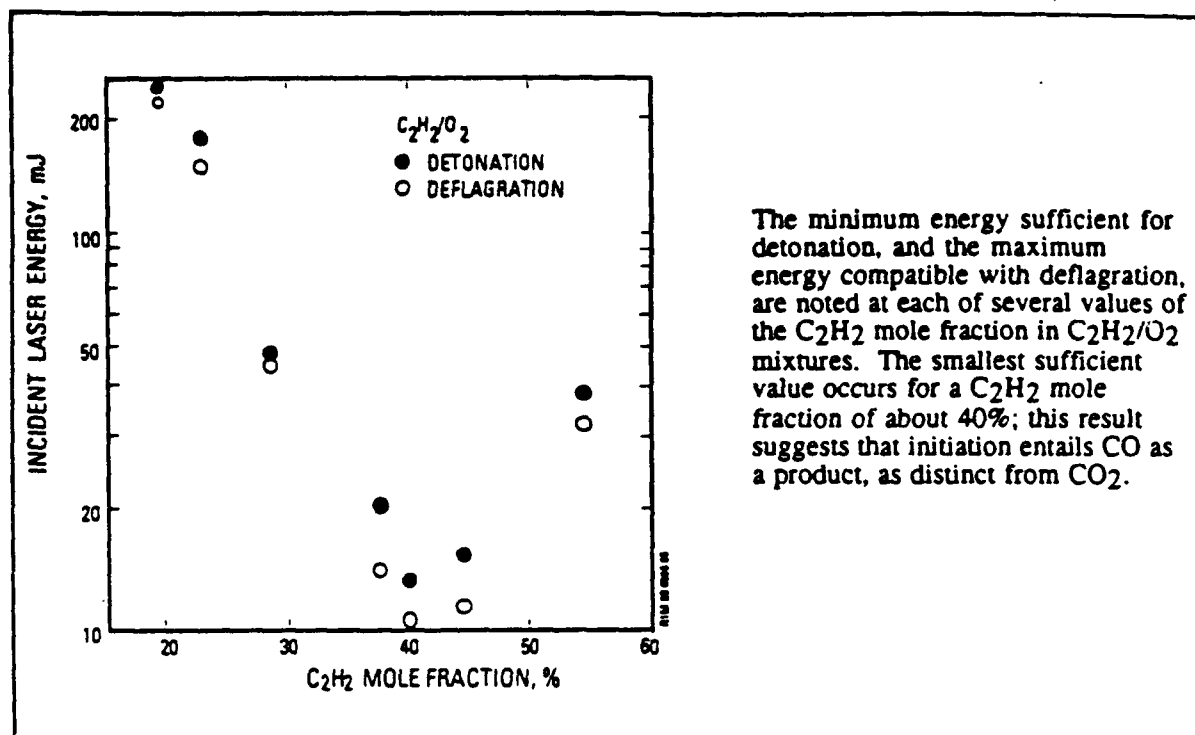


Figure 15. Variation of Critical Energy with Fuel-Equivalence Ratio

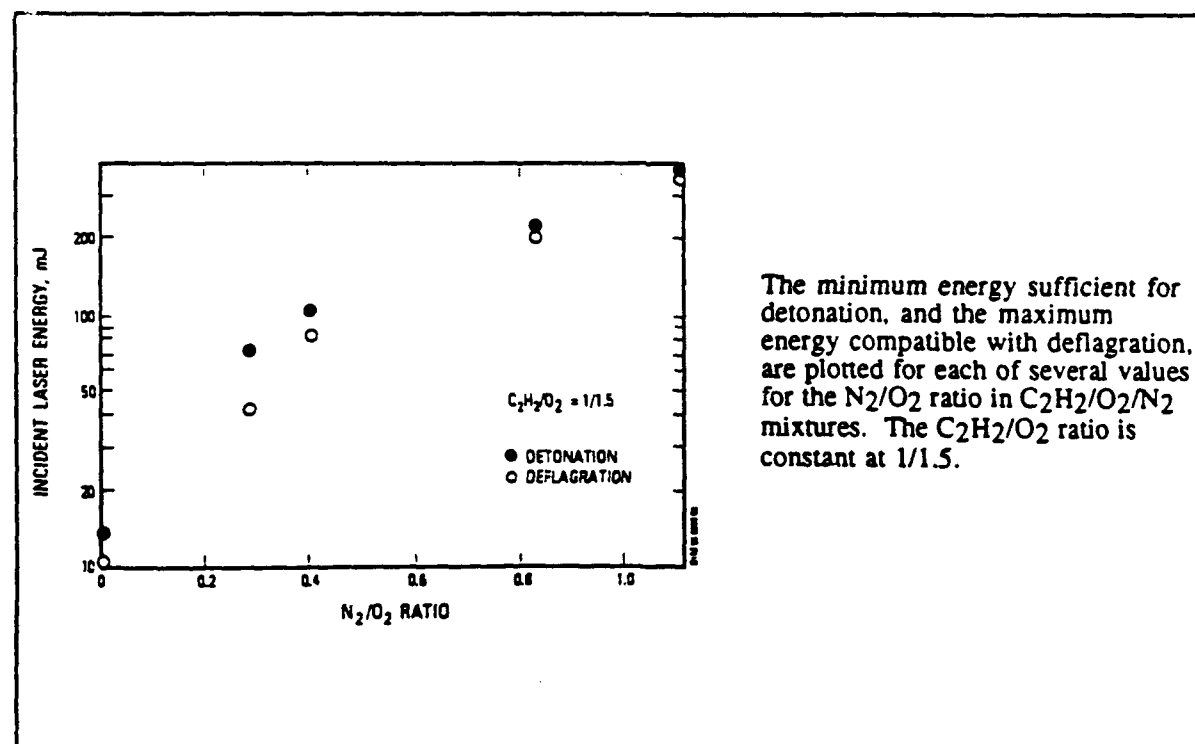


Figure 16. Variation of Critical Energy with N<sub>2</sub> Addition

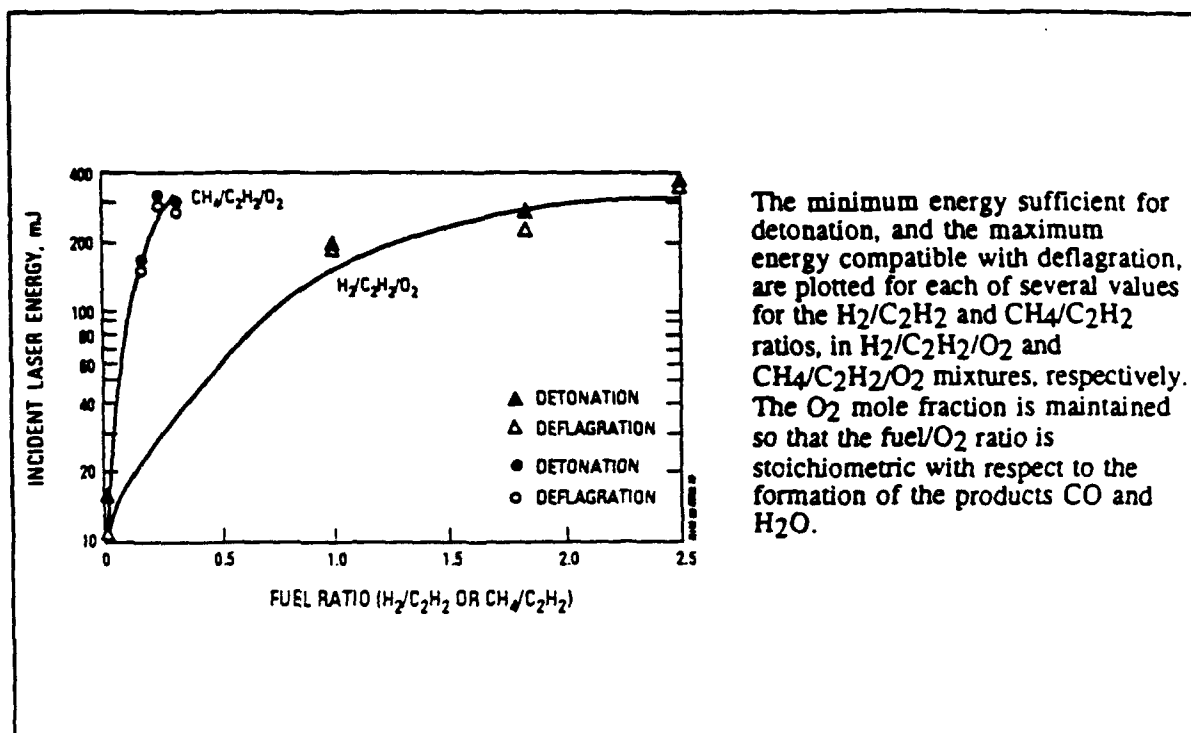


Figure 17. Critical Energies for  $H_2/C_2H_2/O_2$  and  $CH_4/H_2/O_2$  Mixtures

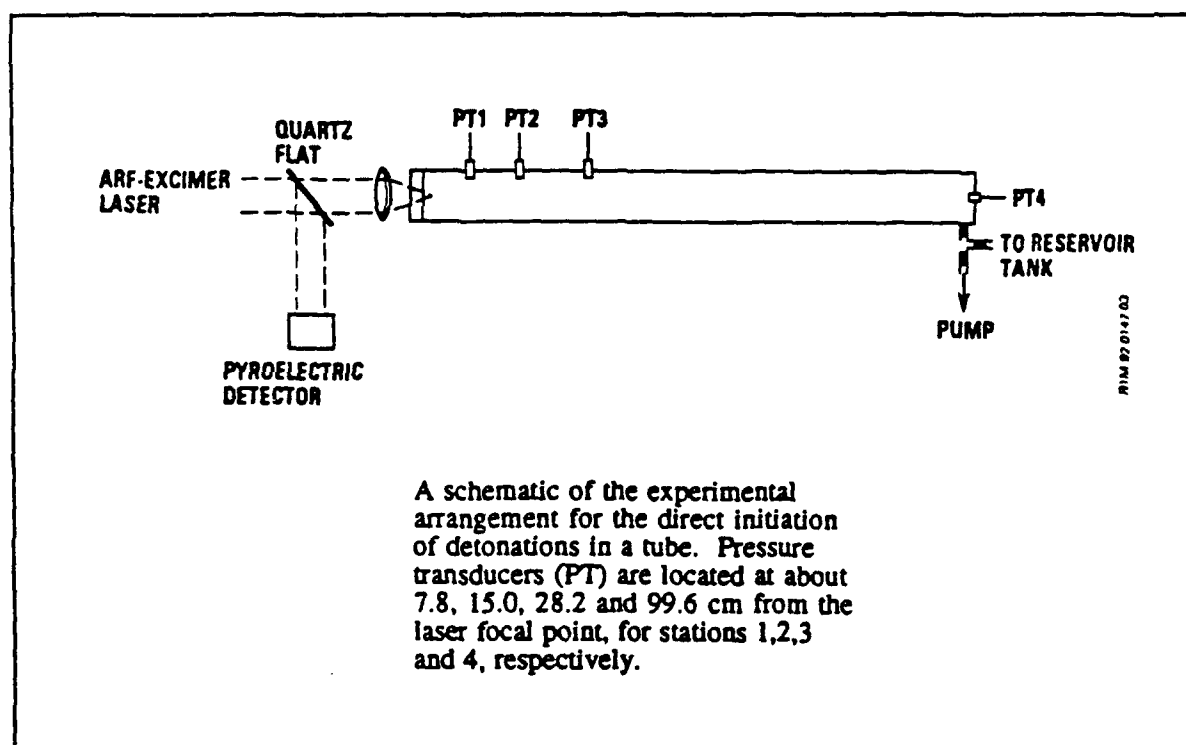


Figure 18. Experimental Arrangement for Initiation of Planar Detonation

(Fig. 19), perhaps by deflagration-to-detonation transition (DDT). The critical energy is found to be inversely proportional to the initial pressure (Fig. 20).

### 3.0 Recommendations: Remaining Issues

We accord a very high priority to a systematic parametric investigation of the direct initiation of detonation in practically interesting combustible mixtures through nonintrusive energy deposition by pulsed chemical laser. By the use of a positive ignition device (the pulsed laser), we incur none of the augmented drag, augmented induction-time delay, and augmented entropy increase arising from purely shock-induced combustion (Cambier, Adelman, and Menees 1989a, 1989b) that is associated with the introduction into a supersonically flowing, reactive mixture of a solid body, inevitably with finite nose curvature and subject to jitter, however the body is supported. The innovative procedure made conceptually possible by laser technology is to deposit sufficiently large energy in a sufficiently large volume in a sufficiently brief time, so that each laser pulse ignites a radially outwardly propagating Chapman-Jouguet detonation wave (Carrier, Fendell, and Chou 1992).

In practice we are interested in not just a single initiation event, but rather in the periodic initiation (with minimal interpulse period) to generate a train of such spherical detonation waves in a supersonic combustible stream. In this way, we stabilize a resulting conical detonation wave and incur minimal entropy rise.

For appreciably supersonic flow, achieving practical combustor length suggests spanning a reactive stream with flame within a short streamwise distance of the combustion-initiation site. Impractically long combustor length is associated with deflagration-to-detonation transition, as distinct from the direct initiation of detonation. Also, the output power of commercially available pulsed lasers of a specific type tends to be bounded, so, among models of specific type, the repetition rate (the number of pulses per second) typically is inversely proportional to the energy per pulse. Thus, a relatively high rate of repetition is correlated with a relatively small amount of energy per pulse. In fact, at high repetition rate, the available energy per pulse may fall below the minimal (critical) value required for the direct initiation of detonation in a given mixture. Consequently, in utilizing a pulsed laser, generating a spherical blast wave that decays to a spherical detonation wave ("overdriving" the initiation process) (Lee 1984) well may be as impractical for present purposes as generating a spherical deflagration wave that later accelerates to a spherical detonation wave ("underdriving" the system). Accordingly, we seek to deposit the minimal energy consistent with virtually instantaneously initiating a spherical wave (Chou, Fendell, and Behrens 1993) that thenceforth propagates radially outward with the Chapman-Jouguet (CJ)-wave speed of a combustible mixture of practical interest, so that we also maintain rapidly repeated deposition (laser operation at a high repetition rate of the laser).

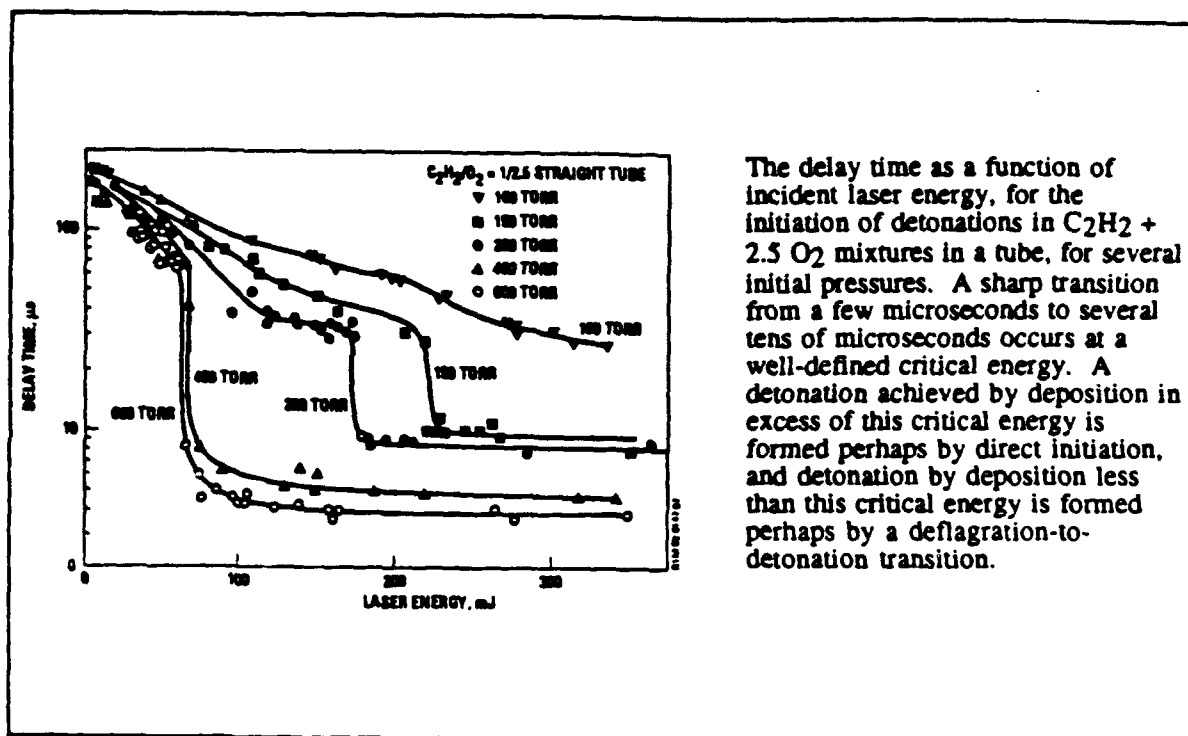


Figure 19. Delay Time as a Function of Incident Laser Energy

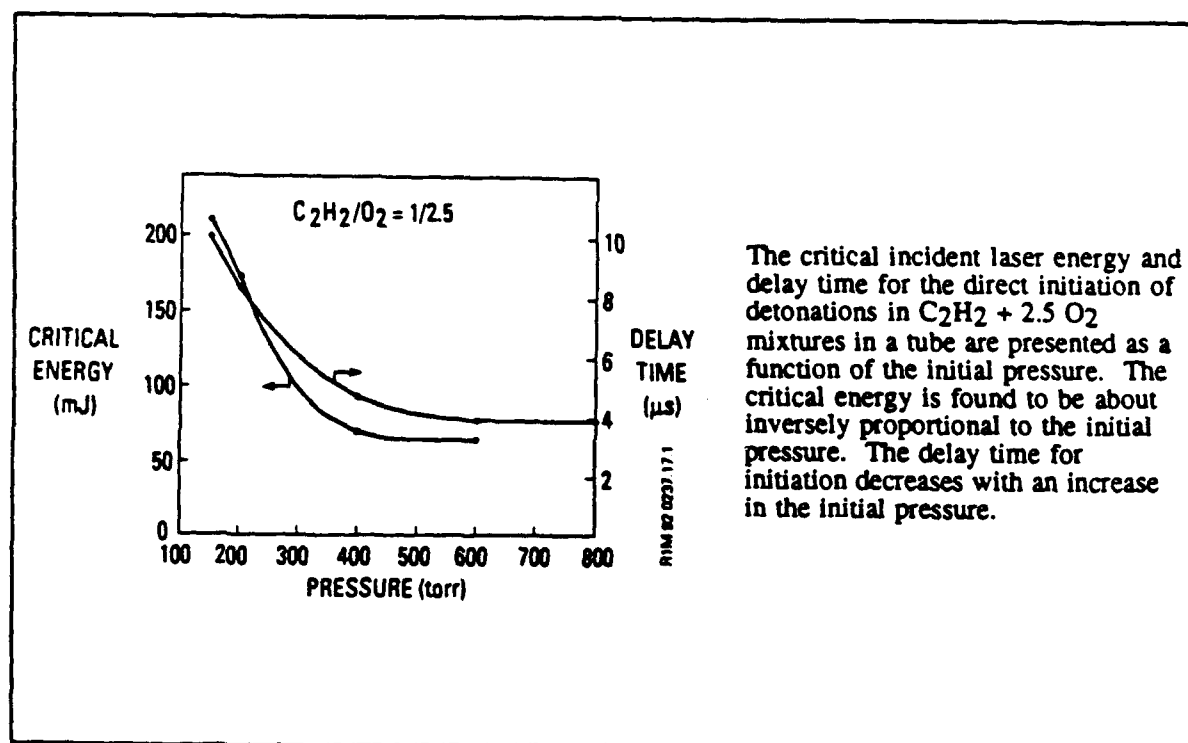


Figure 20. Critical Energy and Delay Time for Planar Detonation as a Function of Initial Pressure

We have systematically explored (Section 2, Experimental Results - Laser-Initiated Detonation) laser photochemistry as a particularly efficient means of achieving direct initiation of detonation (Lee, Knystautas, and Yoshikawa 1978; Chou, Fendell, and Behrens 1993). To exploit photochemistry, we sometimes must add to the fuel-air mixture, at trace-level concentration, a species that is absorptive of the incident laser radiation, and we prefer an additive that photodissociates into highly reactive fragments to promote the chemical reaction. In fact, we prefer that the fuel-air mixture be largely transparent to the incident laser radiation (and such is generally the case for many fuel-air mixtures of practical interest). In such circumstances, the laser beam can propagate with little degradation through the perimeter of the flowing combustible stream, and can be absorbed predominantly at the intended focal site in the "core" of the stream (Fig. 21). This localized absorption is assisted by admixing the sensitizing trace additive only near the centerline of the flowing stream. Of course, once the detonation is locally and instantaneously initiated at the focal site, the detonation thenceforth propagates radially outward through the unsensitized but detonable portion of the mixture, as the mixture is convected downwind.

Standard detailed-chemical-kinetic modeling, after augmentation by the rates and mechanisms related to the initiating photochemical steps, may provide some guidance for the direct-initiation experiments. However, we doubt that time-and-space-resolved computation of the direct nonintrusive initiation of detonation warrants high priority. The reason is that the observed cellular scale on which chemical reaction is completed in actual detonations is a hydrodynamic scale appreciably larger than the chemical-induction-length scale (Lee 1977, 1984). Thus, three-dimensional unsteady computation with detailed chemical kinetics and photochemistry, multicomponent diffusion, and compressible gas dynamics is required for a credible simulation of direct-initiation processes. Such calculations are highly demanding. Furthermore, our experience to date (Chou and Zukowski 1991) with the inability of standard chemical-kinetic packages to predict significant details of the experimentally observed laser initiation of deflagration (whether this inability be due to deficiency in the packages themselves or in our ability to define appropriate initial conditions for applying the codes) implies to us that numerical predictions of the direct photochemical initiation would have limited credibility without experimental verification. Accordingly, the investigation of the parametric dependencies of the direct initiation, by laser, of detonation in mixtures of practical interest ought to be carried out mainly experimentally, with some specific but limited theoretical support. We recommend that most of the theoretical effort be dedicated to clarifying the practical implementation (e.g., Fig. 22) of the high-speed-propulsion possibilities raised by the laboratory demonstration of direct-initiation capability. Presently, although new facilities are being developed at several government installations, there seems no alternative to theoretical investigation of the propulsion aspects of a supersonic combustor based on the laser-initiated conical detonation wave.

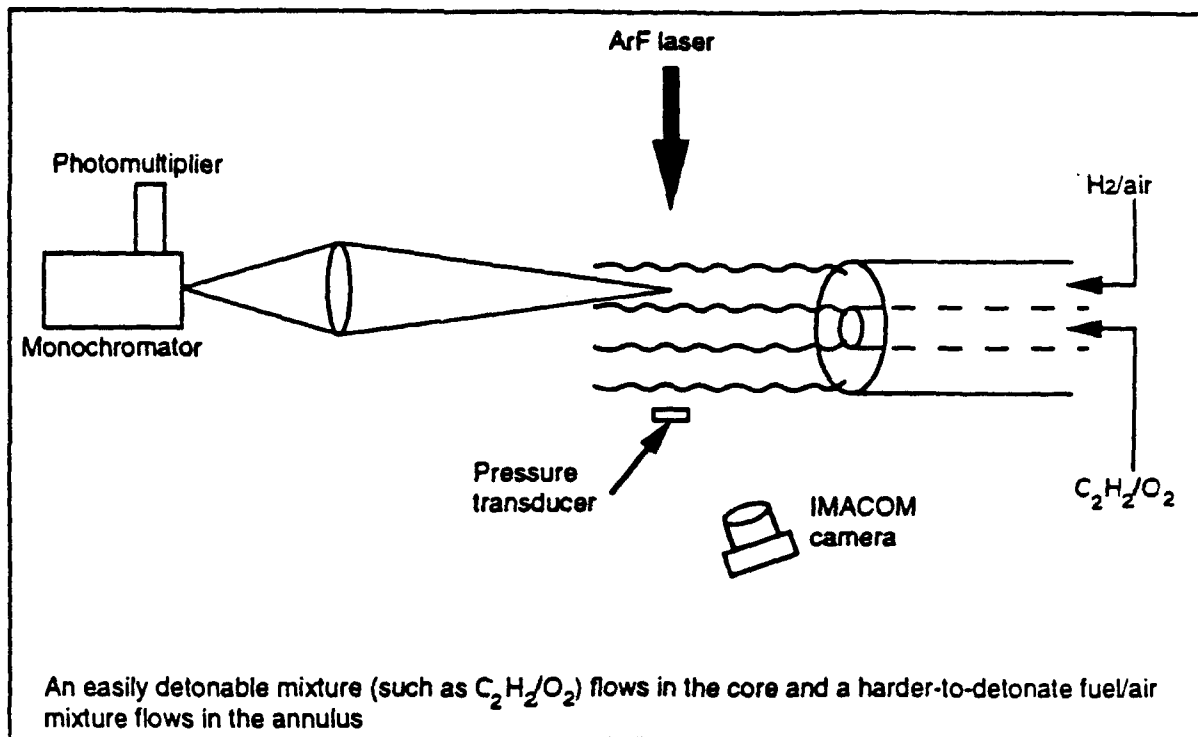


Figure 21. Proposed Experimental Arrangement for Studying Laser Initiation in a Stratified Flow

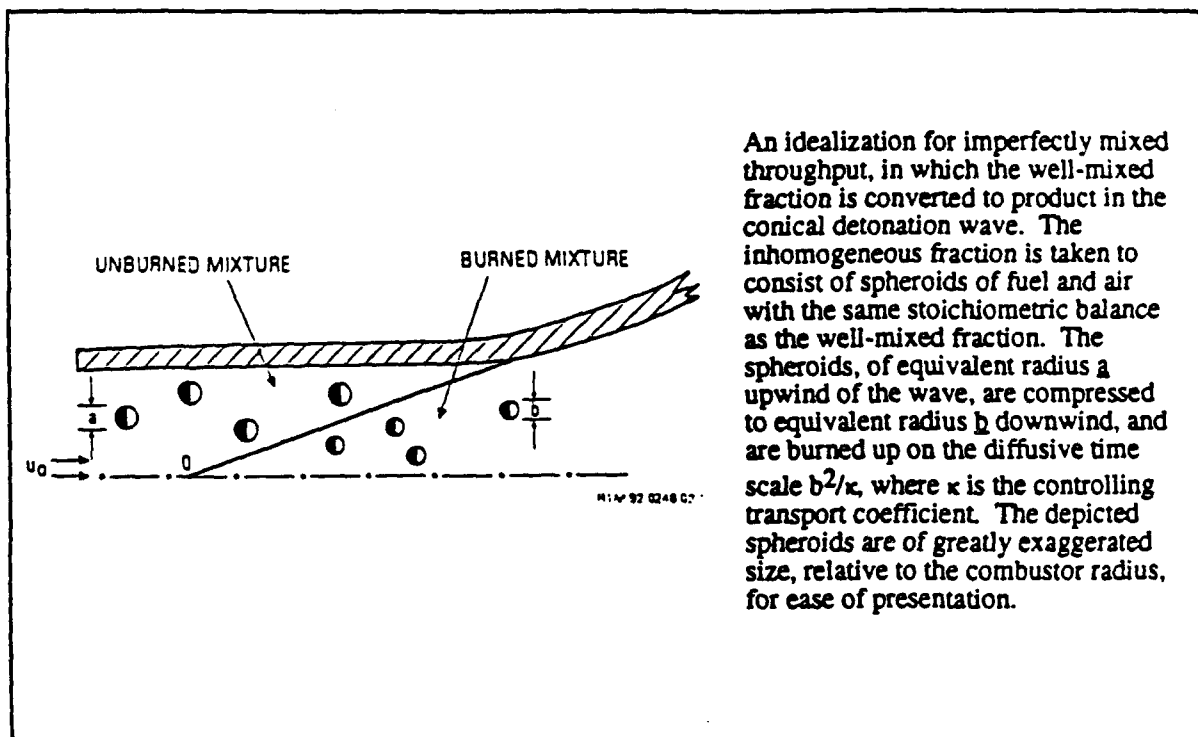


Figure 22. Representation of Imperfectly Mixed Flow for Analytical Modeling



#### 4.0 Contacts with the Hypersonic-Propulsion Community

We have been in fairly continual contact for well over a year with NASA (William Esher and Isaiah Blankson of Code R at NASA Headquarters; Robert Rosen, Gene Menees, Harold Adelman, Jean-Luc Cambier at NASA Ames Research Center), and have toured the experimental facilities at Ames. Some of the Ames facilities are scheduled for upgrading that would make them more suitable for high-speed-mixing experiments--in fact, some limited tests of high-speed fuel-air mixing for an ODWE were carried out by Adelman a few years ago. These seem the most appropriate facilities presently known to us.

More recently, at the suggestion of our contract technical monitor, we contacted Capt. Randall Drabczuk of the Hypervelocity Launcher Technology Branch, Analysis and Strategic Defense Division, Armament Directorate, Eglin AFB, Florida. Capt. Drabczuk is the manager of a program (involving six government employees and outside contractors) aimed at both basic and developmental work on ram accelerators. This program is closely coordinated with the seminal work at the University of Washington, which involved flight of a 38-mm-diameter projectile and which was largely funded by Eglin AFB. It is also closely coordinated with the computational fluid dynamics and 120-mm-projectile ram accelerator testing under way at the Aberdeen Proving Grounds under Army funding. Present plans are to construct at Eglin a ram accelerator for a 90-mm diameter projectile, and background numerical modeling to guide the scaling up of the University of Washington design is being carried on the Eglin Cray computer by staff members of SAIC (Glenn Rolader, Ray Sinha, Sandy Dash, and Brian York). Capt. Drabczuk was familiar with our concept for a laser-initiated conical detonation wave for supersonic combustion, from a presentation that he attended at the Joint Propulsion Conference in Nashville last summer. He noted that work on ram accelerators and ODWEs is mutually beneficial because of the limited experience in the entire field of supersonic combustion. However, he also noted that a ram accelerator was not appropriate for testing our concept.

Capt. Drabczuk also referred us to Prof. Eugene Clothiaux of the Department of Physics of Auburn University, who is developing a shock-tube tunnel to test novel diagnostics, under support from Eglin AFB. The shock tube, with a test-section cross-section of 7.5 cm x 7.5 cm and a test-section length of 3.66 m, is to permit examination of a normal shock in Ar, CO<sub>2</sub>, N<sub>2</sub>, or mixtures thereof, initially at 10-200 kPa. Typically, a shock is to translate at roughly 1 km/s (or Mach number of 5-7 or so), to produce a post-shock state of several tens of atmospheres. While eventually a "two-dimensional" body may be introduced on the floor of the test section, there are no plans to examine detonation waves.

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